Long- and Short-Term Changes in Geospace Driven from Below and Need for Continued Observations

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Workshop on Physical Links Between Weather and Climate in Space and the Lower Atmosphere

International Space Science Institute

Bern, Switzerland

January 22, 2024

Acknowledements

- Workshop Convenors

- NASA TIMED mission and SABER project

- NASA CLARREO mission

- ESA FORUM mission

- My numerous colleagues worldwide

It is a great time to be a Geospace Scientist!

Dawn of the Geospace Climate Era

- **Geospace is defined as the region between ~ 60 km and ~ 1000 km**
- **Increasing carbon dioxide (CO_2) is altering the climate system from the depths of the ocean to the upper edge of Geospace**
- **These alterations have fundamental effects on almost every aspect of human society and the world economy**
- **Geospace is cooling and contracting (as predicted) due to increasing CO_2**
- **The well-documented long-term change in Geospace is a major consideration for the safety and regulation of future constellations of satellites and of orbital debris**
- **The space economy is predicted to be US $ 1 Trillion by 2040!**
- **A *Geospace System Observatory (GSO)* is needed to provide *Geospace Data Records* (GDRs) to accurately assess change with high statistical confidence**
- **Accurate GDRs will inform future space policy, space law, international regulations, and will influence the evolution of the space economy**

See: Mlynczak et al., An Observational Gap at the Edge of Space, Eos, May 2021
https://eos.org/opinions/an-observational-gap-at-the-edge-of-space

Main Point

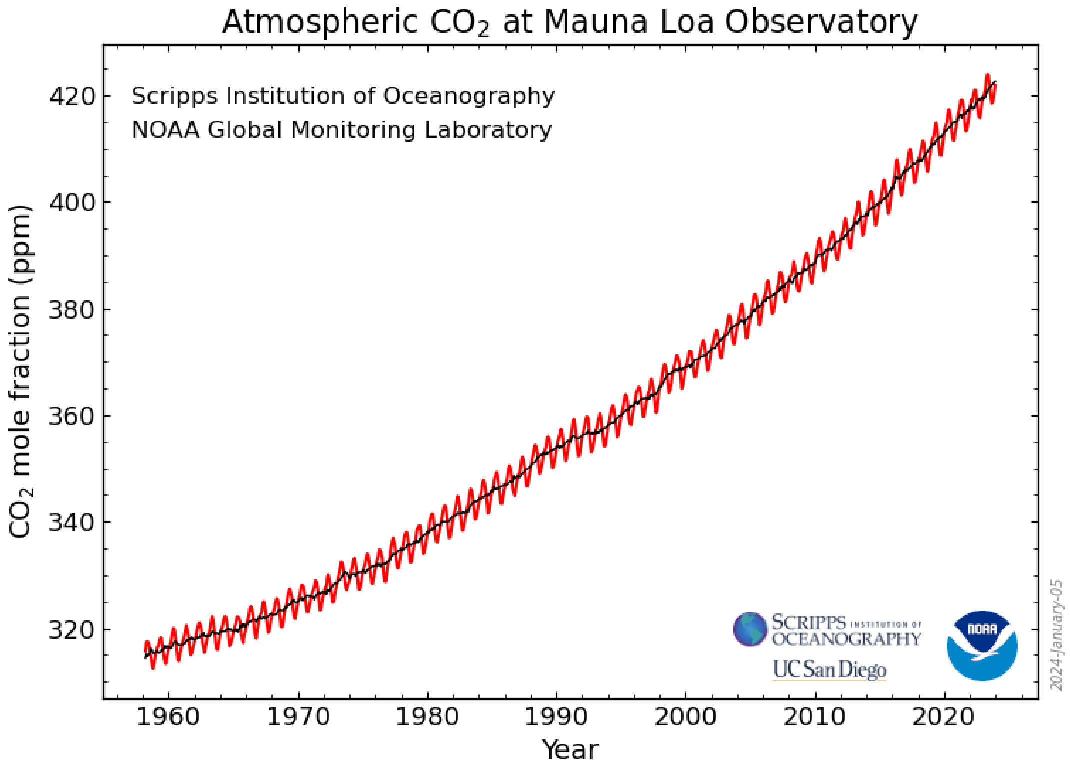
Observing decadal change in Geospace requires great attention to the development of new instruments and new observing systems to provide accurate and consistent scientific results that can confidently guide future economic and policy decisions

Upcoming NASA and ESA climate trend missions can help inform new Geospace observation requirements

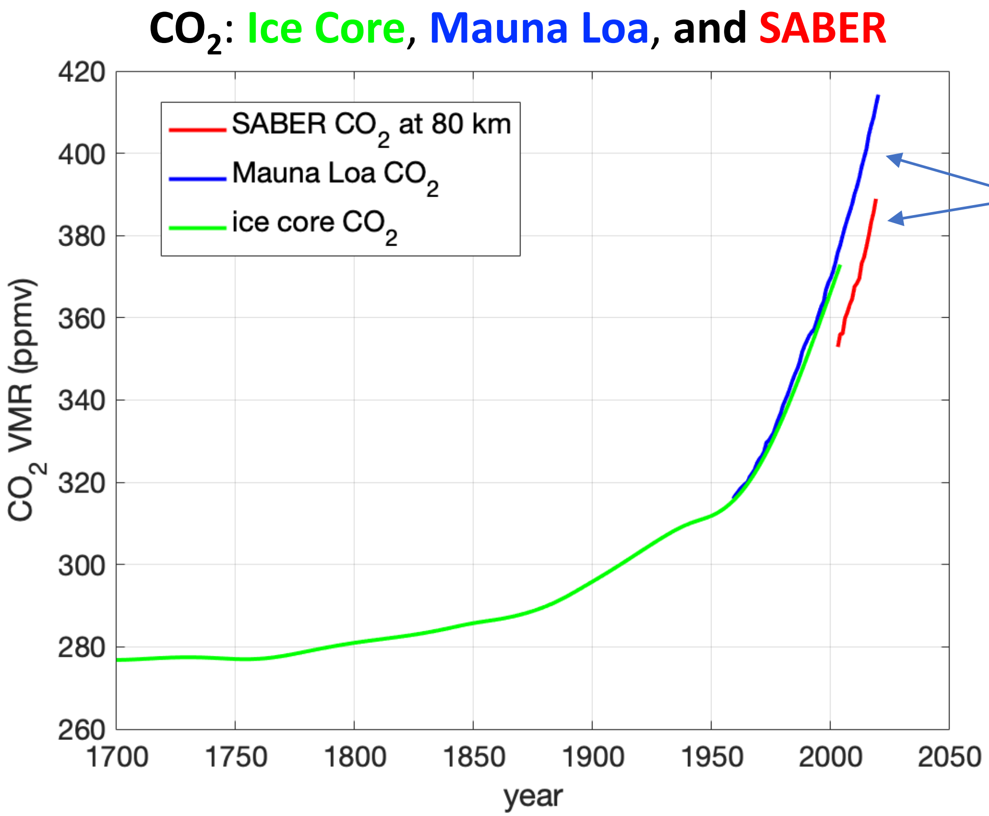
Outline

- Observations of increasing CO_2 in the Atmosphere
- Recent determinations of change in lower regions of Geospace
- Status of existing observations of lower Geospace
- Definition of a Geospace Data Record (GDR)
- Design considerations for a future Geospace System Observatory (GSO)
  - Goal is to measure the trend in a parameter, not just the parameter itself!
- Challenges to achieving trend accuracy – real life examples!
- Questions going forward
- Summary

Increasing Carbon Dioxide at Earth's Surface and in the MLT



CO_2 at Earth's Surface Since 1959



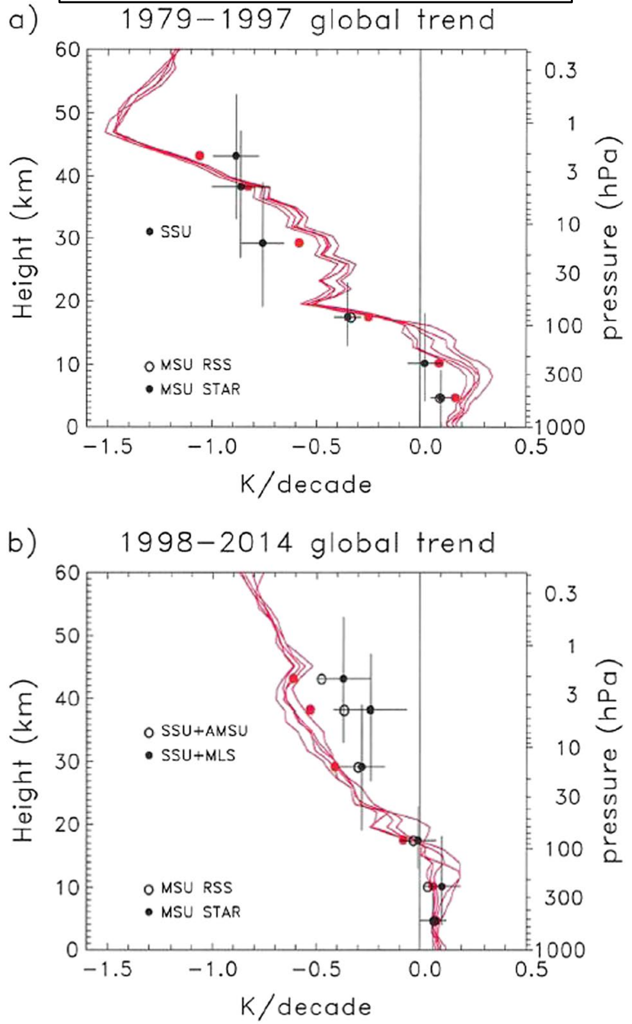
Slopes of SABER and Mauna Loa are ~ identical

CO_2 at Earth's Surface and at 80 km from SABER

CO_2 is Increasing in the MLT at the Same Rate as at Earth's Surface

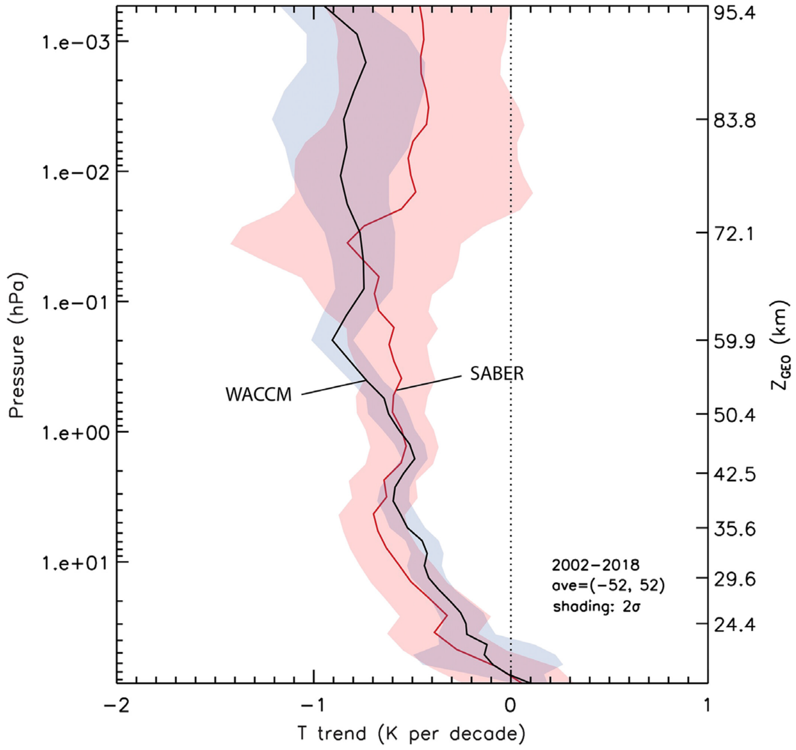
The Cooling and Contracting Stratosphere, Mesosphere, and Lower Thermosphere

Troposphere and Stratosphere



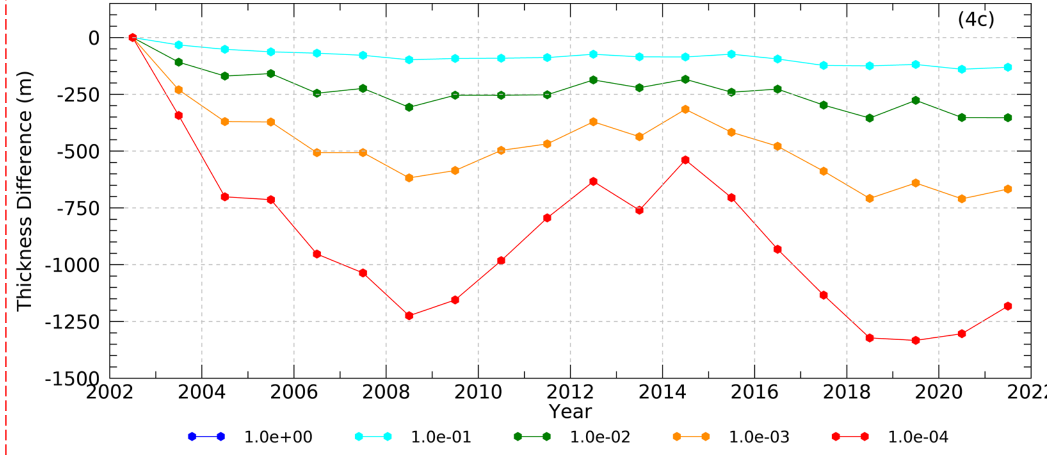
Randel et al., JGR, 2017
https://doi.org/10.1002/2017JD027158

Stratosphere and M/LT Temp



Garcia et al., JGR, 2019
https://doi.org/10.1029/2019JA026909

Thickness of Layers in the M/LT



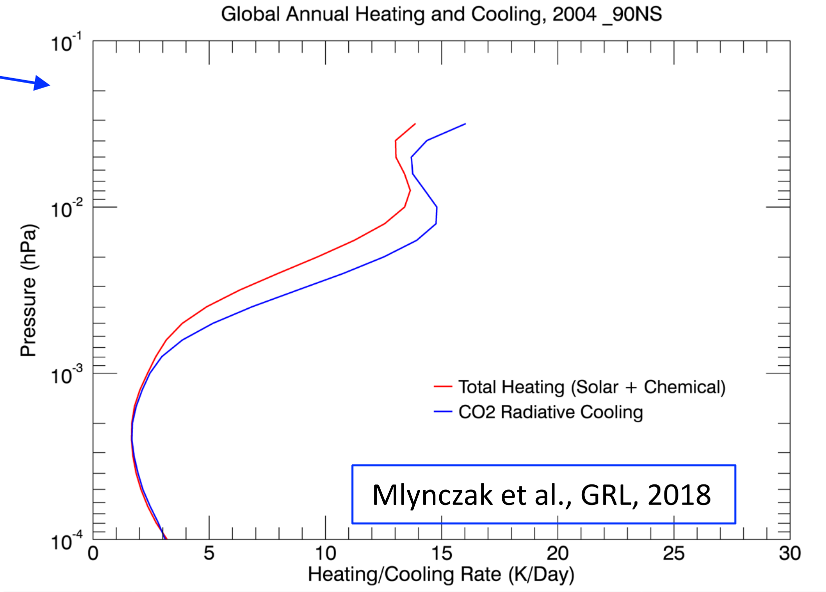
P (hPa)	Thickness* Change (m)	Thickness Trend (m/dec)
10^{-1}	- 118	- 40 +/- 3.7
10^{-2}	- 276	- 77 +/- 13.4
10^{-3}	- 640	- 119 +/- 18.5
10^{-4}	- 1333	- 190 +/- 31.6

*Thickness relative to 1 hPa surface

Mlynczak et al., JGR 2022
https://doi.org/10.1029/2022JD036767

How Does Increasing CO_2 Enable a Reduction of MLT Temperature?

- As CO_2 increases in the MLT, the temperature decreases over time at a rate of ~ 0.5 K/decade
- What is the physical mechanism responsible for this?
- Infrared radiation from CO_2 (15 μm bands) is a fundamental component of the energy budget (and hence, the climate) of the MLT
- Does more CO_2 → more 'cooling', i.e., more IR radiation?
  - NO! Infrared radiation can only increase if an object *warms!*
- As temperature decreases, IR radiation should decrease!
  - If IR radiation decreases, the MLT would warm, opposite of observed
- What is the solution to this conundrum?
- As CO_2 increases, the emissivity of the 15-um bands increases
- On climate (annual, longer) timescales, the MLT can only radiate the amount of energy it receives
- Increasing CO_2 → Increasing CO_2 emissivity → allows the MLT to radiate the same amount of energy but at a lower temperature



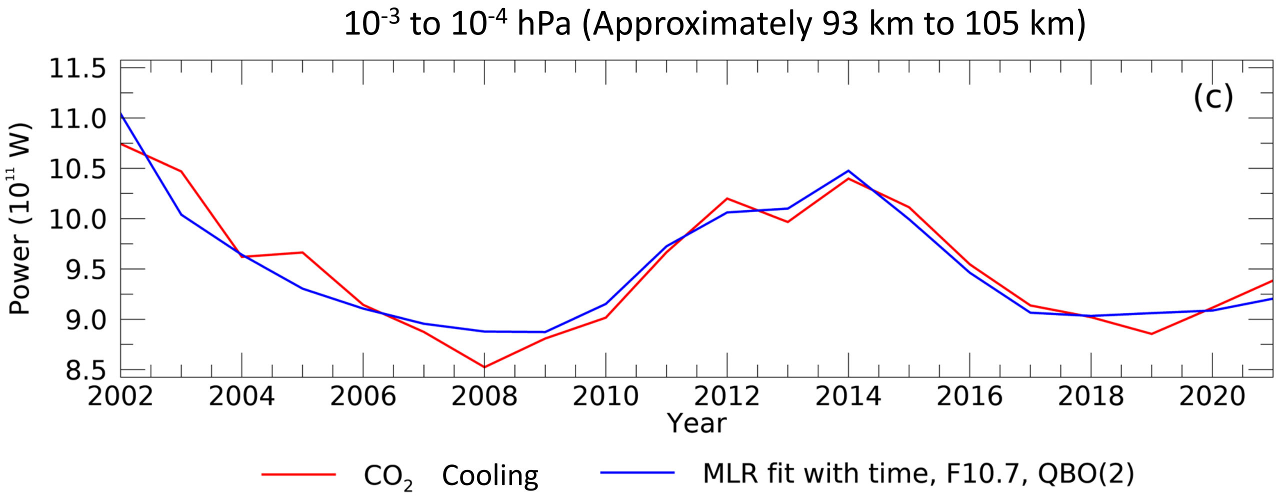
Consequence – there should be zero trend in infrared radiation emitted from the MLT

Trend Analysis of Exiting Longwave Radiation (ELR) from the MLT

- Compute, from the first law, the global annual exiting longwave radiation in Watts from layers within the MLT

$$ELR = \int_{z_1}^{z_2} \frac{\partial Q}{\partial t}\, dz = \int_{z_1}^{z_2} \rho\, C_p\, \frac{\partial T}{\partial t} dz = -\frac{C_p}{g} \int_{p_2}^{p_1} \frac{\partial T}{\partial t}\, dp$$

- Use multiple linear regression of global annual ELR to derive trend in ELR



Derived trend = $(1.48 \pm 1.42) \times 10^{10}$ W/dec, 1-sigma

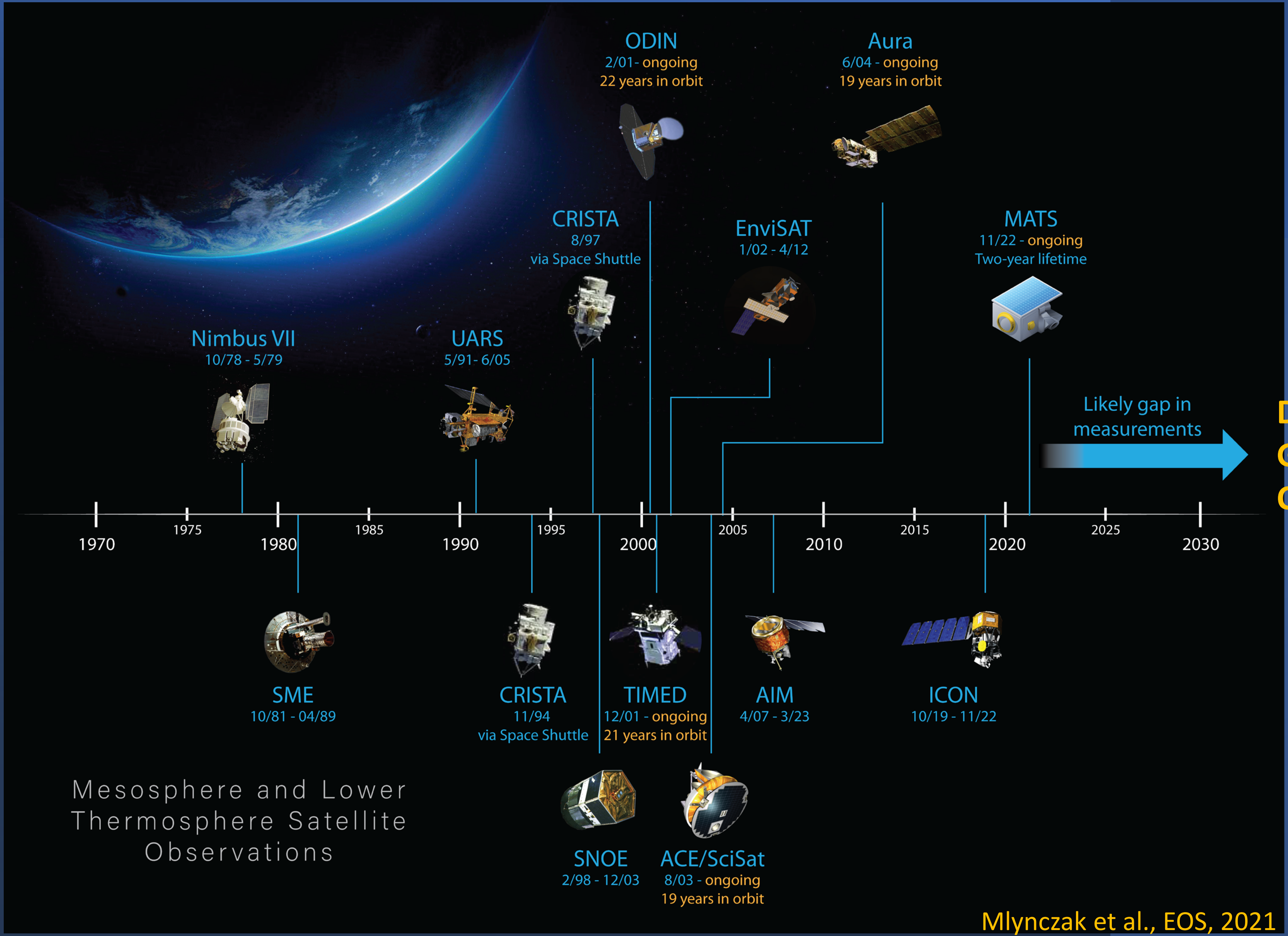
At 1-sigma, trend and trend uncertainty are ~ equal

At 2-sigma, 95% confidence, trend is no different from zero

Analysis of ELR derived from SABER radiative cooling rates indicates zero trend in ELR at 95% confidence in MLT

SABER confirms increasing CO_2 allows the MLT temperature to decrease while emitting the same amount of energy over time

Current and Prior Missions Observing Lower Geospace



DYNAMIC ?

GDC ?

CAIRT ?

Design Considerations for a Geospace System Observatory

Main Point - Addendum

Observing decadal change requires measuring the trend in a parameter

The science measurement requirements are placed on the trend accuracy

Example: MLT Temp Trend is ~ 0.5 K/decade

If, for economic decisions, a 10% trend uncertainty is required,
the uncertainty in the trend must be 0.05 K

If 3-sigma significance is required, the required trend uncertainty is 0.05/3 = 0.017 K

The CLARREO Infrared sensor has a 0.1 K, 3-sigma uncertainty requirement

The requirements for Geospace change are not known yet, but must be determined

major problems in atmospheric radiation: an evaluation and recommendations for future efforts

Atmospheric Radiation Working Group (ARWG)

Bulletin of the American Meteorological Society
October, 1972

1.4. Determination of climatic trends—While radiation observations from satellites are presently not precise enough to determine the small globally-averaged variations that would correspond to climatic changes, the effort should be made to extend the accuracy so that these subtle variations can be observed. The requirements for this purpose are not well established, but accuracies of the order of ± 1 % *(or better)** for the radiation budget of the planet appear necessary. Furthermore, the system, with the required accuracy, will have to be maintained on a continuing basis for long periods (probably decades) in order to detect and verify any long-term climatic trends which may be present.

* Kellog, W. W., *The Earth's Climate From Space*, Pergamon Press, ***1974***

The Concept of a Geospace Data Record

- What is a Climate Data Record (CDR)?
- A CDR is "*a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change*" (*National Research Council*, 2004)*

- Define the Geospace Data Record (GDR):
- *A time series of measurements of sufficient length, consistency, and continuity to determine geospace variability and change (Mlynczak et al., GRL, 2023)*
- Why do we need a special term?
- Measuring change, *typically by measuring the trend* (rate of change with time) of a parameter, after removal of natural variability (e.g., the solar cycle), is a vastly different proposition than simply measuring the parameter itself
- Defining and producing GDRs will set these data apart from others as sufficient quality for trend detection and potential economic/legal/societal decisions/action for Geospace

**National Research Council. (2004). Climate data records from environmental satellites: Interim report. The National Academies Press. https://doi.org/10.17226/10944*

How do we create Geospace Data Records (GDRs)?

- Characteristics of a GDR – Length, Consistency, and Continuity
  - Length – the data record must be long enough to determine the trend with high confidence
  - Consistency – datasets from consecutive sensors must be seamlessly joined
    - *High accuracy* – as defined for measurement of the specific trend – is essential
  - Continuity - Overlap of successive sensors is required to ensure a seamless transition in accuracy/calibration
  - Stability – Calibration and Algorithms must not change (real life examples to follow!)
    - Type 1 – Calibration Stability
    - Type 2 – Algorithm Stability
    - Type 3a - Orbit stability for space/time sampling – NASA's Aqua and Terra satellites kept within 2 minutes!
    - Type 3b – Orbit stability for algorithm stability

    All major real-life examples of orbit and algorithm stability come from trying to determine trends!

  - Many lessons learned from development of tropospheric trend missions (e.g., NASA CLARREO mission; ESA TRUTHS and FORUM missions)

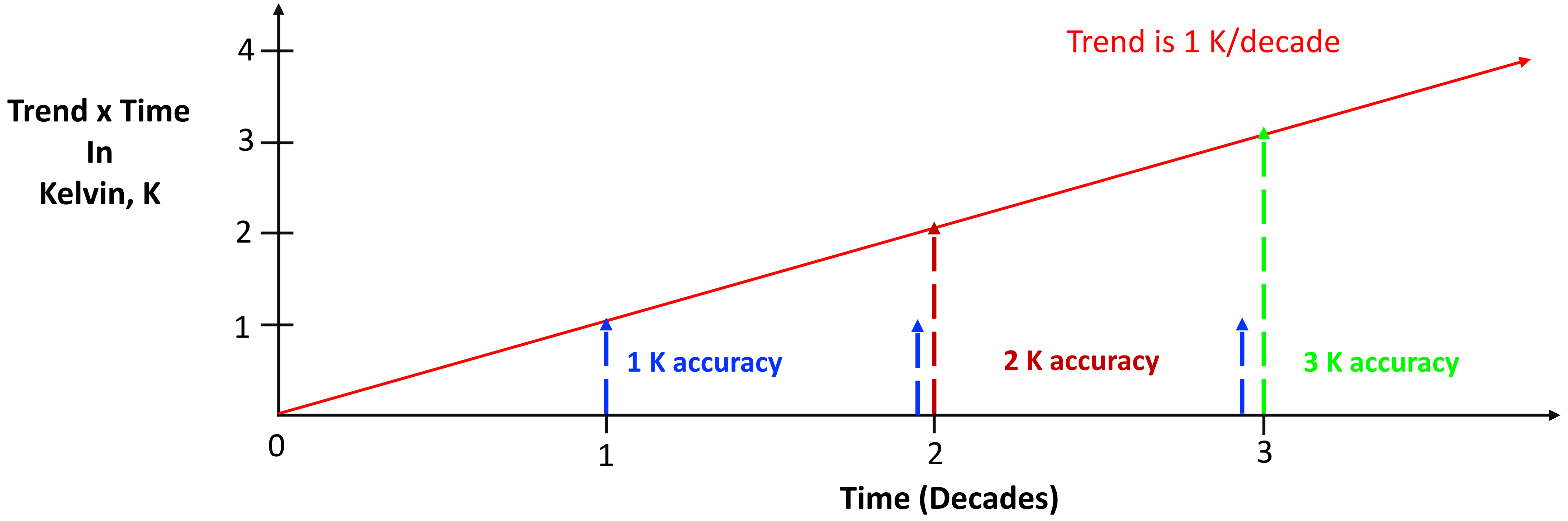
  - GSO must be designed to measure trends in parameters, not just the parameter itself!

Challenges to Measurement of Trends: Accuracy

- **Trend measurement requires much higher absolute accuracy than normal process measurements**
- **Example: SABER-derived Temp. trends in mesosphere are ~ 0.5 K per decade (+/- 0.17 K, 1-σ)**
- **If a sensor has an absolute accuracy of 1 Kelvin, it will take more 2 decades (2 decade x 0.5 K/decade) for the trend to be seen above the accuracy and uncertainty of the sensor**
- **SABER assumes *stability* – that the rate of change/degradation in calibration is zero, and that the calibration error 'cancels out' when calculating temporal differences**
- **Comparison of SABER against *stable* standards (GPS temperatures) show a possible calibration drift (calibration instability) of about 0.15 K/decade (1-σ)**
- **The combined trend uncertainty and calibration stability uncertainty is about 0.23 K/decade (1-σ)**
- **At two-sigma, the combined trend uncertainty is 0.46 K, about 92% of the calculated trend**
- **At three-sigma (99% confidence), the trend uncertainty is greater than the trend**
    - **Climate science missions (CLARREO, TRUTHS) require 3-σ. Particle physics requires 5-σ to 6-σ to identify new particles**
- **Higher accuracy, higher stability, and higher confidence will be required for future GDRs**

Example 1 – Accuracy and time to detect

Illustration of Accuracy and Time to Detect Trends

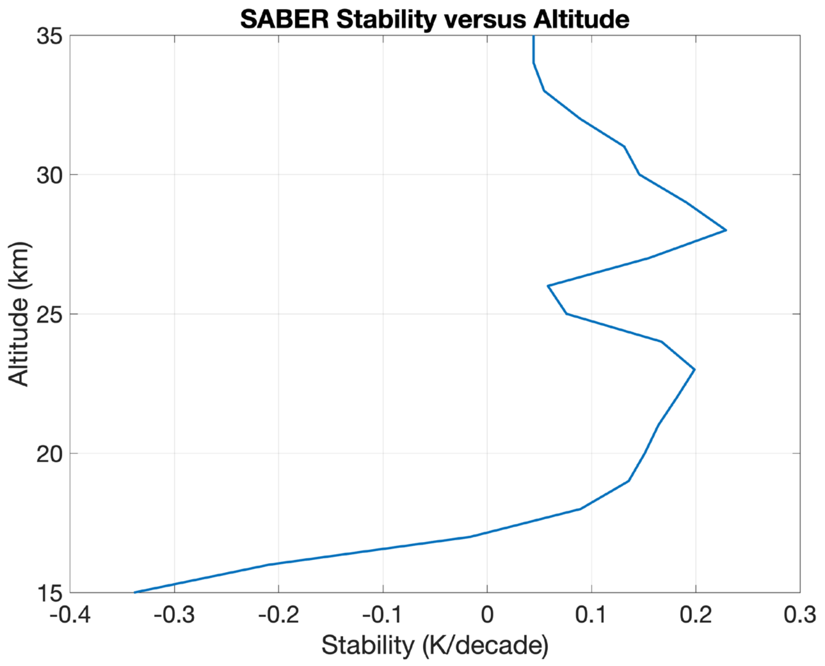


- Measurement accuracy determines the length of time needed to detect a trend
- In the illustration above, the trend emerges above the accuracy after 1 decade
- After 2 decades, the trend is twice the accuracy, and so on
- Conclusions:
  - There is a minimum amount of time required to detect a trend
  - Improving accuracy shortens time to detect trends
- See CLARREO mission paper in BAMS: https://doi.org/10.1175/BAMS-D-12-00149.1

Example 2 – Stability of Calibration - SABER

Example: Calibration and Stability of SABER

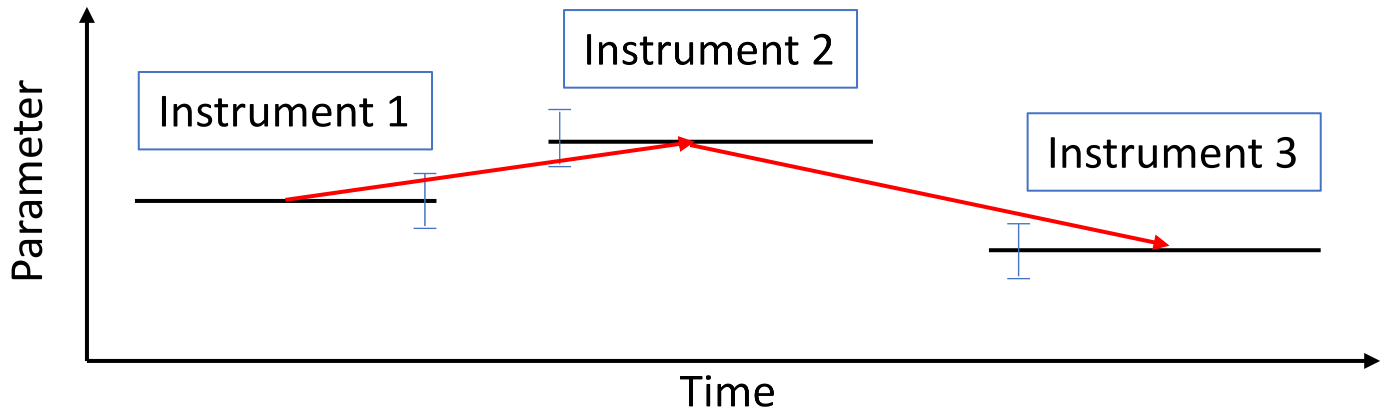
- Example: SABER temperature accuracy is 2 K to 5 K between 50 km and 90 km
  - The trend in temperature derived from SABER is about 0.5 K per decade in this region
  - It would require 4 to 10 decades (2/0.5 to 5/0.5) for the trend in temperature to exceed the accuracy of the temperature measurement
- The typical approach in almost ALL trend studies is to assume the instrument calibration is stable – i.e., unchanging over time
- Mlynczak et al., (2020) showed that SABER calibration likely has a negative drift in its calibration



- Comparison of <u>stable</u> COSMIC (GNSS-RO) temperatures with SABER
- COSMIC minus SABER differences are positive → SABER temps. are slowly decreasing relative to a stable (COSMIC) reference
- SABER likely has a small calibration ‘instability’ of 0.1 to 0.2 K/dec
- This is a large fraction of the potential trend – 20% to 40% of the trend may be due to drift in the instrument
- GSO will need ability to demonstrate calibration stability over decades

Example 3: Continuity and Need for Overlap of Record

- **Typically, at current levels of calibration accuracy, <u>gaps in space-based in CDRs</u> (and likely future GDRs) lead to very large uncertainties in derived trends from the combined records**



- **Three identical instruments with identical calibration uncertainties with gaps in the record**
- **Is there a trend or is the system changing back and forth?**
- **Climate community (Loeb et al., JGR, 2009, CERES Instruments) have shown gaps add significant uncertainty such that trend error is ~ comparable to expected trend**

Conclusions: Overlap of successive instruments is essential
Enables calibration of successive instruments to be tied to their predecessors
The relative calibration is preserved at the level of the absolute calibration of the first sensor

Example 4 – Orbit Instability → Algorithm → False Trends

- The Microwave Sounding Unit (MSU) instruments between 1979 and 1995 exhibited a ***cooling*** of the lower troposphere
- This result was unexpected and opposite to the radiosonde record, other data, and expectations of warming in climate models
- These issues caused substantial rancor in the climate community
- Independent analyses discovered that MSU algorithms for generating the lower troposphere temperature were dependent on orbital parameters such as orbit altitude
- Satellites carrying MSU routinely lost altitude
- The neglected orbital-decay, once corrected, resulted in a MSU temperature indicating lower troposphere warming consistent with other data records
- Station-keeping can be a significant cost driver in a system design

Wentz and Schabel, Nature, v 394, 1998
https://www.nature.com/articles/29267

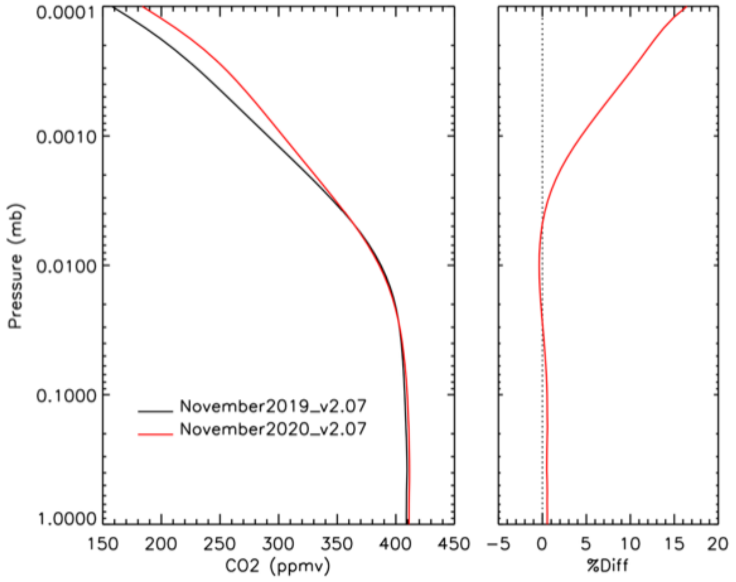
Effects of orbital decay on satellite-derived lower-tropospheric temperature trends

Frank J. Wentz & Matthias Schabel

Remote Sensing Systems, 438 First Street, Suite 200, Santa Rosa, California 95401, USA

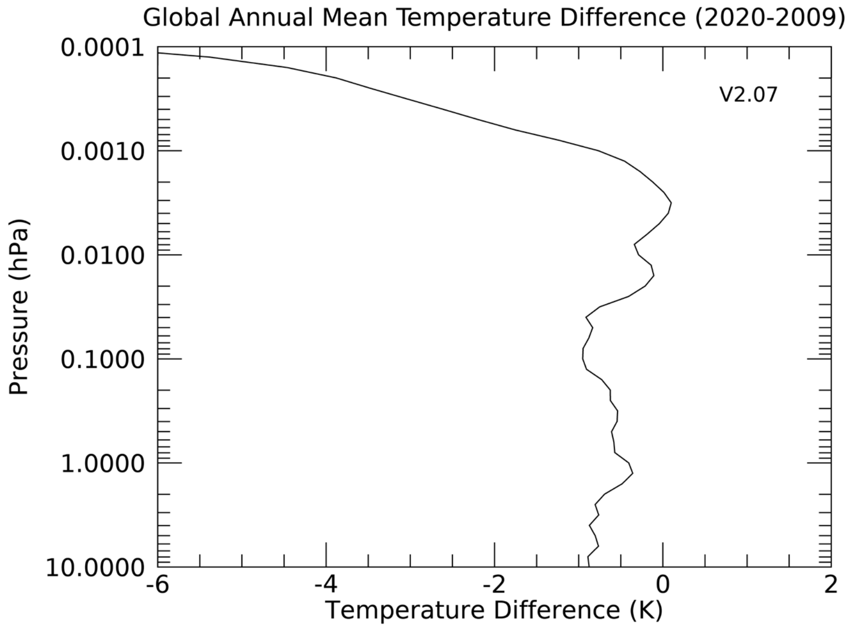
The 17-year lower-tropospheric temperature record derived from the satellite Microwave Sounding Unit (MSU)[1–3] shows a global cooling trend, from 1979 to 1995, of −0.05 K per decade at an altitude of about 3.5 km (refs 4, 5). Air temperatures measured at the Earth's surface, in contrast, have risen by approximately +0.13 K per decade over the same period[4,6]. The two temperature records are derived from measurements of different physical parameters, and thus are not directly comparable. In fact, the lower stratosphere is cooling substantially (by about −0.5 K per decade)[5], so the warming trend seen at the surface is expected to diminish with altitude and change into a cooling trend at some point in the troposphere. Even so, it has been suggested that the cooling trend seen in the satellite data is excessive[4,7,8]. The difficulty in reconciling the information from these different sources has sparked a debate in the climate community about possible instrumental problems and the existence of global warming[4,7,9]. Here we identify an artificial cooling trend in the satellite-derived temperature series caused by previously neglected orbital-decay effects. We find a new, corrected estimate of +0.07 K per decade for the MSU-based temperature trend, which is in closer agreement with surface temperatures. We also find that the reported[7] cooling of the lower troposphere, relative to the middle troposphere, is another artefact caused by uncorrected orbital-decay effects.

Example 5 – Algorithm Instability → False Trends in SABER



SABER requires CO_2 density to retrieve T

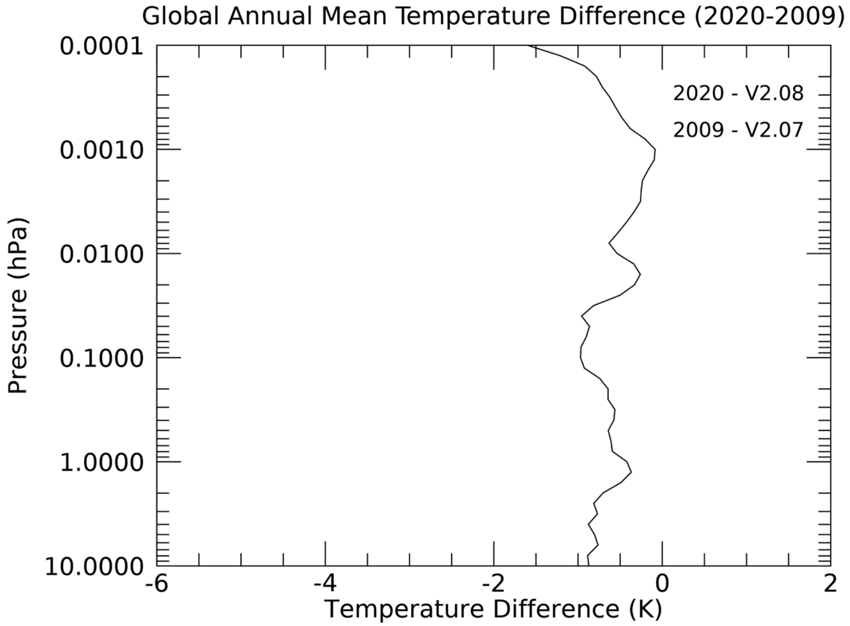
In Nov. 2019, added WACCM CO2 from a different version of the model than previously used



Increased CO_2 $p < 0.003$ hPa

Change in CO_2 equal to two decades of natural CO_2 increase

Resulted in temperatures substantially colder in 2020 solar min than 2009 solar min



Replaced CO_2 2019 onward with prior WACCM version

Changes in Temp from 2009 to 2020 are in accord with expectations

Mlynczak et al., GRL, 2023

Need for High Statistical Significance

Gravitational Waves
Laser Interferometer Gravitational-Wave Observatory LIGO

PRL 116, 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Results at 90% Confidence

Higgs Boson
Large Hadron Collider LHC

Physics Letters B 716 (2012) 1–29
Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb
ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

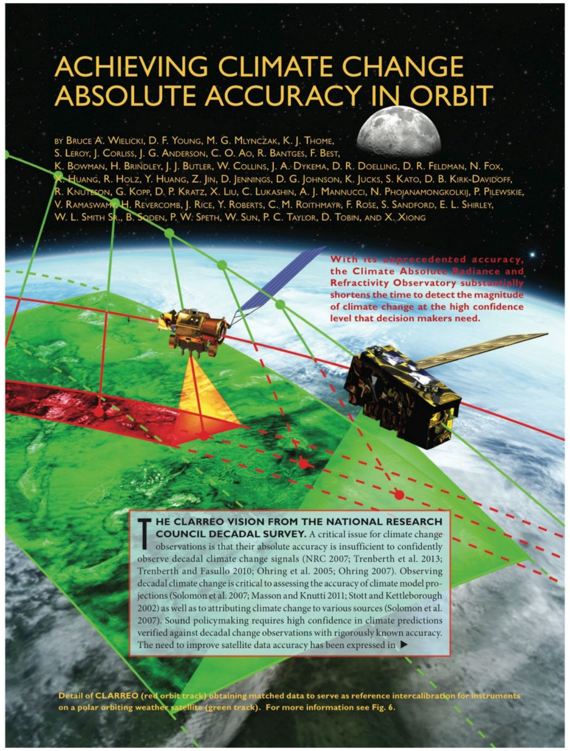
Article history:
Received 31 July 2012
Received in revised form 8 August 2012
Accepted 11 August 2012
Available online 14 August 2012
Editor: W.-D. Schlatter

ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Results at 5.9 sigma

Tropospheric Climate
Climate Absolute Radiance and Refractivity Observatory "CLARREO"



Results at 3-sigma

High statistical significance required for it to be "science" and for societal/economic/policy decisions

Challenges ⟷ Opportunities

- Can we design a viable Geospace System Observatory to confidently determine long-term change?
- How do we achieve higher accuracy in space-based Geospace measurements, particularly of in-situ sensors?
- What role will machine learning play in this effort?
- How do we involve various national agencies dealing with long-term space debris concerns?
- How do we constructively involve the ‘space economy’
- Can we avoid being viewed as climate alarmists?
- How do we convince review boards and funding bodies that systematic measurements are fundamental (Nobel-caliber) science deserving of decadal support?

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It is a great time to be a Geospace Scientist!

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